

Mixed-mode ventilation and air conditioning as alternative for energy savings: a case study in Beirut current and future climate

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Abstract The aim of this work is to assess the use of mixed-mode ventilation for a typical office building in Lebanon and consequently reduce Heating Ventilation and Air Conditioning (HVAC) energy consumption in the observed current and under the future projected climatic conditions. Mixed-mode cooling is considered a compromise between the insufficient natural ventilation and the expensive year round-operated HVAC. A control algorithm is set for windows and HVAC system to ensure mixed-mode operation. Dynamic simulations are performed on a typical office building in Beirut City under the mixed-mode operation in the present and the future using commercial IES-VE software. The results of the software were validated against measured HVAC and total energy consumption of the typical office base case with conventional mechanical system. The results of the simulations are evaluated in terms of potential reduction in energy consumption under the present and the future weather data. Finally, a lifecycle cost analysis is performed

for the proposed system, and its payback period is computed. Under present construction practices and weather data, 31% annual energy savings were achieved using mixed-mode system. Under future 2050s projected weather data, annual energy savings of 21% was attained with a payback period of 3.8 years.

Keywords Climate change · Adaptive comfort · Control algorithm · Mixed-mode ventilation

Abbreviations

C_n	System running cost
CO_2	Carbon dioxide
COP	Coefficient of performance
$\langle dbt_{omax} \rangle_m$	Monthly mean maximum temperature under current weather conditions ($^{\circ}\text{C}$)
$\langle dbt_{omin} \rangle_m$	Monthly mean minimum temperature under current weather conditions ($^{\circ}\text{C}$)
GHG	Greenhouse gases
HADCM3	Hadley Center Coupled Climate Model
HVAC	Heating ventilation and air conditioning
$I_{h,o}$	Current hourly solar horizontal irradiation energy (Wh/m^2)
IES-VE	Integrated Environmental Solutions–Virtual Environment
IPCC	Intergovernmental Panel on Climate Change
MENA	Middle East and North Africa
N	Holding period of the NPV
n	Running year
NPV	Net present value
NW	North West Orientation

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ppm	Parts per million
r	Discounted rate of return
r_o	Current relative humidity data (%)
SE	South East Orientation
T_{in}	Indoor temperature
TM _Y	Typical meteorological year
T_{op}	Indoor operative temperature
T_{OUT}	Outdoor temperature (°C)
T_{HL}	Adaptive cooling upper limit set-point temperature (°C) defined in the ASHRAE 55 Adaptive Comfort Model (2013)
T_{LL}	Adaptive heating lower limit set-point temperature (°C) defined in the ASHRAE 55 Adaptive Comfort Model (2013)
T_{AC}	Mechanical system air conditioning set point temperature (°C)
T_{He}	Mechanical system heating set point temperature (°C)
t_{omdb}	Monthly mean of the current dry bulb temperature
t_{omwb}	Monthly mean of the current wet bulb temperature
U -value	Overall heat transfer coefficient (W/m ² /K)
UHIE	Urban Heat Island Effect

Greek symbols

ΔJ_{mwb}	Monthly mean change in wet bulb temperatures (°C)
$\Delta J_{h,m}$	Monthly percentage mean change in solar horizontal irradiance (%)

Introduction

One major global concern nowadays is climate change, which was subject to numerous studies. These studies aimed at the quantification of future global weather trends. For example, the Intergovernmental Panel on Climate Change (IPCC) quantified an average global surface temperature increase of 0.9 to 4.8 °C by the years 2100s under different CO₂ emission scenarios (high emission, medium emission, low emission) (IPCC 2014). This surge in surface temperature affects largely the building energy consumption.

Buildings consume currently 40% of the global energy consumption (Ürge-Vorsatz et al. 2012) of which offices represent one of the most energy-intensive constructions (Pérez-Lombard et al. 2008). Particularly in the Middle East, buildings consume 27% of the total energy

consumption (Ürge-Vorsatz et al. 2012; Pérez-Lombard et al. 2008), and it is expected to rise at an annual rate of 3.2% (Pérez-Lombard et al. 2008; Williams et al. 2012), hence draining global energy resources needed for development and increasing greenhouse gases (GHG) emissions. There is a need to reduce energy consumption in office buildings in the present and future especially for HVAC systems due to their strong connection to the outdoor climate. To reduce HVAC energy consumption without implications on thermal comfort and indoor air quality, studies have assessed the use of passive systems (such as natural ventilation) instead of the conventional air-conditioning systems to cool buildings (Pfaferott et al. 2004; Pollock et al. 2009; Bianco et al. 2009; Cardinale et al. 2003). Natural ventilation is found promising in moderate climates offering an acceptable indoor environment at low-energy consumption (Pfaferott et al. 2004; Annan et al. 2014). In the Middle East, 52% of all the hours of the year is expected for natural ventilation usage in Lebanon under current weather data (Annan et al. 2014), and around 10 to 40% energy savings are achieved in Dubai-UAE due to the use of natural ventilation in the moderate months (Taleb 2015).

In office spaces, thermal comfort is crucial for worker productivity, and the ASHRAE comfort standard 55–81 (ASHRAE 2013a, b) recommends thermal comfort acceptability by 80% of occupants. However, natural ventilation is not sufficient to provide desired comfort all the year, and its use is limited to moderate seasons. An alternative to natural ventilation is to use mixed-mode or hybrid systems. This alternative makes maximum use of natural ventilation with supplementary use of mechanical systems in extreme weather conditions (Ezzeldin and Rees 2013; Bianco et al. 2009; Griffiths and Eftekhari 2008). It controls windows and HVAC systems to harness natural ventilation, minimize energy use and provide occupant comfort. As “Open Plan” offices are preferred to be controlled automatically rather than manually for better comfort (Schulze and Eicker 2013; Deuble and de Dear 2012), the hybrid system alternates between systems in an automatic manner as per the comfort temperatures allowed for natural ventilation (Ji et al. 2009). This system has several advantages of which are the following: (i) extending the applicability of natural ventilation to a longer period of the year due to the control of windows opening (Alves et al. 2015) and (ii) the embedded natural ventilation part of the system results in human adaptation to a wider range of outdoor conditions (Alves et al. 2015; Wang and Greenberg 2015; Humphreys and Nicol 1998). Research

conducted on this system showed interesting results and proved its reliability (Alves et al. 2015; Schulze and Eicker 2013; Tuohy et al. 2007; Rijal et al. 2008; Inkarojrit and Paliaga 2004). However, these studies have been mostly concerned with application in temperate climates and countries of Europe, and limited assessments are conducted for the climate of the Middle East (Ezzeldin and Rees 2013). Moreover, the operation and performance of the mixed-mode cooling system in the present might be limited in the future, facing climate warming, and this should not be neglected during the system's assessment especially that climate warming has become a quantified fact rather than a theory. Thus, the assessment of the system's future performance is crucial to insure its reliability.

In this study, a hybrid system (mixed-mode system) is assessed for applicability in the area of Lebanon, Middle East. Lebanon was chosen being a country with a moderate climate which allows the use of such systems. The objective of this study is to perform a quantitative assessment of the energy-saving potential of hybrid systems in office buildings in Lebanon under present and future climates. The approach followed consists of (i) performing dynamic simulations under present and future climatic conditions for a typical office building in Lebanon, (ii) deducing its energy consumption patterns over the years, and (iii) performing a life cycle cost analysis of the system. The raised concern regarding the future and the lifecycle cost is due to the fact that the Middle East is prone to significant increased human activities leading to serious climate warming effects (Lelieveld et al. 2002). This affects the energy-saving potential of the proposed system in the future. Dynamic simulations are performed on a typical office building in Beirut Lebanon under the hybrid mode approach in the present and the future using IES-VE software (IES Virtual Environment 2015).

Methodology

In this study, the potential of hybrid system in providing thermal comfort for workers is assessed for the present and the future, and its energy consumption is simulated. The dynamic simulation software IES-VE (IES Virtual Environment 2015) capable of performing complex thermal modeling of natural ventilation and hybrid systems is used in the simulations. The software was validated and adopted by many researchers (Pollock et al. 2009; Annan et al. 2014; Azhar and Brown 2009) for similar studies.

A set of design parameters are taken as inputs into IES-VE software, these parameters are pivotal to the building

performance. The parameters include the present and future weather files of the country, the natural ventilation scheme, geometry, building orientation, construction material, windows specifications, occupancy density, equipment heat dissipation, schedules for occupancy, and equipment and the designs of the heating and cooling systems. In addition, a detailed control algorithm for the windows and the air-conditioning (AC) system is developed to operate the hybrid system. The function of this control is to provide occupants comfort and save energy by simple alternation between the windows operation and the AC system's operation.

Lebanon current climate data and weather file

Located on the eastern side of the Mediterranean (latitude 33° 49 N; Longitude 35° 29 E) with a 220 km long coast line (Haddad et al. 2014), Lebanon has a climate characterized by hot summers and mild rainy winters. Beirut is the capital of the country and is the largest urban conglomerate in Lebanon. This city is prone to a hot microclimate caused by the Urban Heat Island Effect (UHIE) (Ministry of public works and transport 2005). Lebanon annual temperature ranges between 5 and 38 °C during the various seasons. Moreover, humidity levels in the area vary between 55 and 70% with highest humidity level witnessed in Beirut City (Ghaddar and Bsat 1998).

To be able to assess mixed-mode ventilation in Lebanon, the hourly weather file of the country is a major input of the software IES-VE. In this study, the weather file used in the simulation represents the latest version of the Typical Meteorological Year (TMY3) weather file for Lebanon for the TMY3 ranging between 1991 and 2005. The weather file is generated in this study using the *MeteoNorm* software (2015) as has also been used by many researchers (Kalvelage et al. 2014; Radhi 2009; Ineichen 2006). A TMY weather file is generally a combination of weather parameters derived from previously measured weather data (over a period of 10 to 30 years) of which typical descriptive months are combined. These months have weather characteristics that are the most commonly encountered over the years, and they are assembled using the Finkelstein-Schafer method (Jentsch et al. 2008). Since the aim of this study is to compare the annual average energy consumption of the mixed-mode system with the energy consumption of conventional air-conditioning techniques, the annual averages must exemplify the energy consumption pattern that is expected in Lebanon. Thus, they need to be typical averages rather than a 1 year energy consumption set representing solely a single year (which might be

rather extreme than representative). For this purpose, researchers have used TMY datasets for similar studies (Kalogirou 2001). Moreover, since future weather data have to be generated in the remainder of this study, and future data cannot be generated based on a single year hourly dataset, especially that no particular year can have a perfect description on the actual country's climate characteristics of the country, thus TMY sets are needed. The use of TMY datasets for similar purposes was recommended and validated in previous studies (Skeiker 2004; Wang and Chen 2014; Jentsch et al. 2008). In particular, TMY data was validated by Skeiker (2004) for a 10-year period using measured data from 1981 to 1990 of four meteorological parameters of temperature, relative humidity, wind velocity, and global solar radiation for the city of Damascus. The reported P values were higher than 0.05 of each of the four parameters at 0.95, 0.99, 0.84, and 0.81, respectively, with confidence level of 0.95.

Future weather data generation

Future Lebanon hourly weather data are needed for the future simulations. These weather data are estimated for the 2050s (average increase over the years 2040 to 2069) using the IPCC HADCM3 (Hadley Center Coupled Climate Model). HADCM3 makes use of the location of a country, along with the world CO₂ emission scenario to deduce the climate change pattern it will undergo (Intergovernmental panel on Climate Change (IPCC) 2016). The CO₂ emission scenario assumed for this study is A2 which describes (i) a world with high population growth where the local identities are not much changed, (ii) a more regionally than locally oriented economic development, and (iii) a slow technological change. More description of the scenarios and of the HADCM3 model can be found on the IPCC official website (http://www.ipcc-data.org/sres/hadcm3_download.html). HADCM3 provides the variation in monthly mean wet bulb temperatures, monthly mean dry bulb temperatures, monthly mean diurnal temperature range (maximum and minimum dry bulb temperature), relative humidity, and monthly percentage mean change in solar irradiance over certain grid points on the earth, and these grid points can be interpolated to get the exact target location (Johns et al. 2003).

The morphing method developed by Belcher et al. (2005) consists of using previous climate observations (TMY datasets), to downscale HadCM3 future monthly projections into future hourly weather files (Belcher

et al. 2005). For this study, a morphing tool “Climate change world weather generator” was used to produce the future 2050s weather files using the HadCM3 parameters interpolated onto the country's grid points and using the TMY datasets of the country. This morphing tool bases its calculation on (Belcher et al. 2005) equations and proved reliable in previous climate projection studies (Holmes and Reinhart 2011; Costa 2014; Peng and Elwan 2013; Yi and Peng 2014; Skeiker 2014).

Developing windows and HVAC control algorithm

The target of windows and HVAC system control algorithm in hybrid ventilation buildings is to provide occupants comfort and fresh air. To define occupants comfort in unconditioned buildings, the ASHRAE 55 adaptive comfort model (Brager and de Dear 2001) was developed. This model defines a comfort range established based on a comprehensive database of survey locations that includes the Middle East (Ezzeldin and Rees 2013). However, the adaptive comfort model only applies to naturally ventilated buildings and recommends that hybrid buildings get evaluated under Fanger's heat balance approach for more restrictive results (Brager and de Dear 2001). One reason behind this restriction might be that mixed-mode buildings are not subject to sufficient studies while setting this standard (De Dear and Brager 2002). In contrast, subsequent studies including regions in the Middle East have recommended the application of adaptive models in mixed-mode buildings rather than Fanger's model (Ezzeldin and Rees 2013; Ji et al. 2009; Aggerholm 2002; Ezzeldin et al. 2009, 2008). As a result, the adaptive approach is applied in evaluating the performance of the mixed-mode system and in setting the control parameters of this study.

The ASHRAE 55 adaptive comfort model suggests monthly varying temperature limits upon which occupants are supposed to be 80% comfortable under natural ventilation (Brager and de Dear 2001). The 80% acceptability is adopted in this study, and according to it, Eqs. (1) and (2) for natural ventilation cooling and heating set-point temperatures are set (Alves et al. 2015; Wang and Greenberg 2015) as follows:

$$T_{HL} = T_{out} \times 0.31 + 21.3 \quad (1)$$

$$T_{LL} = T_{out} \times 0.31 + 14.3 \quad (2)$$

where T_{HL} is the upper 80% acceptability limit describing the highest set-point for natural ventilation in degrees Celsius. T_{LL} represents the monthly lower 80%

acceptability limit describing the lowest set-point temperature for natural ventilation in degrees Celsius, and T_{out} represents the monthly mean outdoor temperature in degrees Celsius. Several hybrid ventilation control strategies were developed as per the humans comfort expectations for hybrid ventilated buildings (Ezzeldin and Rees 2013; Schulze and Eicker 2013; Wang and Greenberg 2015; Olesen and Brager 2004). In this study, a window control algorithm is described for optimum use of natural ventilation and thermal comfort.

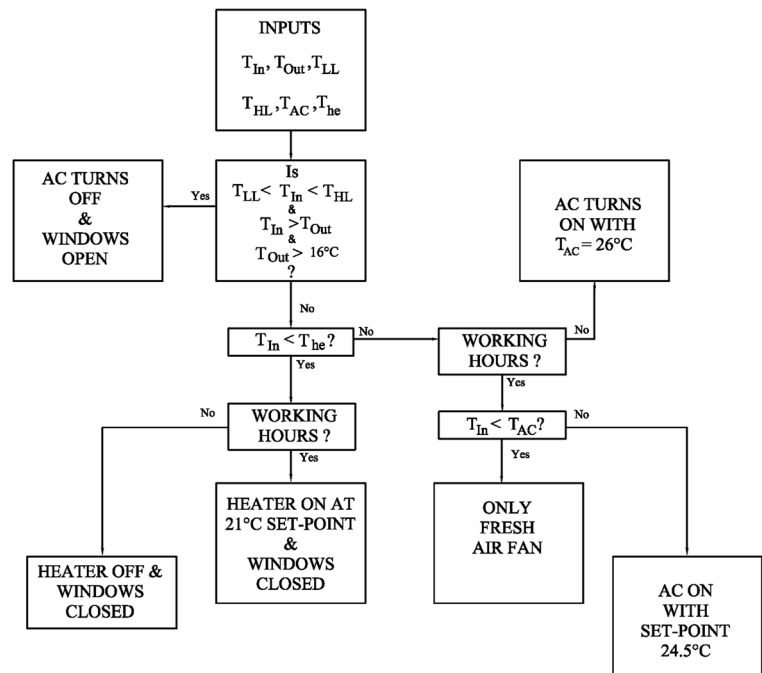
The operation control algorithm is designed to be applicable to both winter and summer for simplicity and it is similar to the algorithm followed previously by Wang and Greenberg (2015) and is illustrated in Fig. 1. When the indoor temperature is acceptable (between T_{LL} and T_{HL}) and is higher than the outdoor temperature, this condition is favorable to open the windows and turn off the AC system. However, when the outdoor temperature is lower than 16 °C (indicative of winter conditions), even if the indoor temperature is between T_{LL} and T_{HL} , the windows remain closed. This restriction is imposed on the system to avoid heat loss to the outside during winter condition. Furthermore, a proportional bandwidth of 2 °C is used to linearly open or close windows each time divergence of indoor temperature from the natural ventilation set-points is detected. During the working hours, the algorithm applies with 24.5 °C cooling set point (T_{AC}) and 21 °C

heating set point (T_{he}). The 24.5 °C is used in our system instead of the base case setpoint temperature to avoid discomfort due to sudden temperature variation at the alternation between systems. This was previously performed in Ezzeldin and Rees (2013) study and allowed by Brager and de Dear (2001). At these setpoint temperatures, the simulation results fall strictly within the limits defining 80% acceptability which is in line with ASHRAE standard 55–81 recommendations for continuous AC operation. In our hybrid system, the fresh air flowrate provided is delivered by a constant air volume fresh air fan (on as long as the windows are closed during working hours); the fan is connected to the AC supply ducts and turns on even if the AC unit is off. The same control algorithm applies to non-working hours, but when windows are closed and the indoor temperature is above 26 °C, the AC will be on and operate at 26 °C during cooling season to avoid overheating due to internal equipment and it will always be off during the heating winter season.

Case study: representative office building description (base case)

A typical open plan (large open space) office built in Beirut was chosen for this study for the purpose of establishing base case energy consumption and assessing mixed-mode

Fig. 1 Windows and HVAC control algorithm



ventilation. Being open plan where manual operation of windows is difficult, the office under study serves as a good test case for controlled hybrid ventilation principle. This office was built according to the typical building features used in the country. It is located on the fifth floor of a 25-year-old building in the capital of Lebanon, Beirut. The office is distanced by 60 m from the surrounding buildings in North-East and by 6 m from the surrounding building in the South West. Described below are the features of the office (Fig. 2).

- Rectangular single Zone space at roof level with a total area of 832 m², an occupied area of 690 m² and a height of 3.7 m
- SE to NW building axis

- Sixty percent glazing on the south-west façade and 11% on the north-east façade
- Glazed surfaces are closed all the time even though operable

The largest area with the highest occupancy is the offices' area containing 49 employees. Other areas are not occupied except at defined times (ex. kitchen only during lunch, etc.). The office's operation schedule is from 08:00 to 17:00 all over the year during the week-days. Lights and equipment follow people's schedule except for computers (on continuously). Total lighting power of 5000 W is distributed in the offices. The major electrical equipment of the office are one laser printer

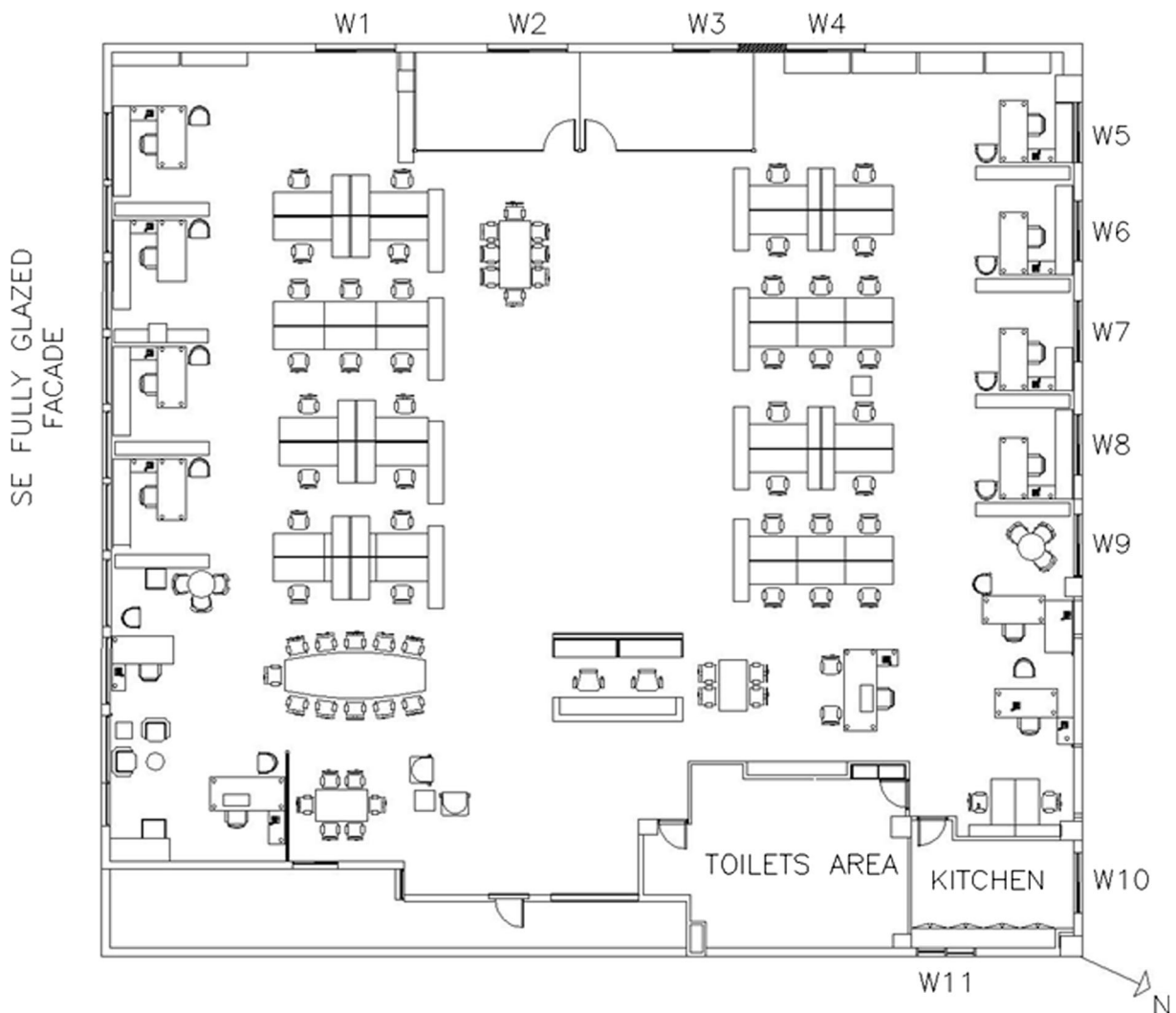


Fig. 2 Typical open plan office layout in Beirut

(88 W heat dissipation), one fax machine (20 W heat dissipation), and 42 desktop computers. The computers have a 2GB RAM and are assumed to have a heat dissipation rate of 60 W/computer. The office's construction materials and glass properties are summarized in Table 1 as per the actual office construction which is similar to the common practice in the country. The infiltration in the office was assumed at two air changes per hour. The AC system of the base case building is a direct expansion (DX) unit, operational all year long with AC set-point of 23 °C during the working hours, 26 °C during non-occupied hours operation, and 22 °C heating set point during the working hours. The fresh air flow rate of the office is determined according to the recommendations of ASHRAE standard 62.1 ventilation requirements for office spaces (2.5 L/s/person and 0.3 L/s/m²).

Cooling system

The cooling system of the existing office consists of the following: three roof package heat pumps (ducted) with heating/cooling capacities ranging between 35 and 40 kW serving the open office area. Each unit consumes around 11 to 13 kW electricity (rated power). The outdoor roof package unit fans are constant air volume fans and blow an air volume of 11,300 m³/h each, of which 470 m³/h is fresh air (untreated fresh air). A separate exhaust centrifugal inline fan serves the toilets and kitchen area.

The suggested mixed-mode cooling system consisted of utilizing the same cooling system of the existing office but with modifications on its control. This was proposed to reduce the system refurbishment cost. This way, sensors and actuators are used to turn on and off the cooling system, control the set point temperatures of the system, and open and close the office's windows (using electrical window motors). Temperature sensors are

used to sense the indoor conditions, the actuators operate the system such as each time the indoor temperature goes above or below a predefined bound (that vary monthly), and an action is taken as per the algorithm shown in Fig. 1.

Electricity consumption

The electricity consumption of the actual office was monitored on monthly basis for both the total value and the HVAC equipment for the year 2013. They will be used in the validation of the software for the base case. The electricity consumption peaked in the summer months of July and August with values of 13.58 and 13.40 MWh. The lowest electricity consumption occurred during the months of February and March with 7.20 and 6.93 MWh per month, respectively. This low consumption is due to the fact that those months are classified as moderate months where HVAC energy consumption is low. The electricity consumption in the winter was 8 MWh.

Results

Validation of future weather data

The accuracy of the future weather data is a pivotal issue not to be ignored in the simulation process as the whole system's future assessment is based upon it. As the monthly dry-bulb temperature is one major input in energy simulations, the validation of this weather parameter is crucial for an accurate prediction of the system's energy performance. In order to validate the model, the strategy of Wang and Chen (2014) was followed; two historical TMY data sets were used: (1) TMY2 (1961–1990) and (2) TMY3 (1991–2005). These data sets were first collected using the MeteoNorm software.

Table 1 Typical office construction material and corresponding *U*-values

Construction element	Construction materials (in to out)	<i>U</i> -value (W/m ² /K)
External walls	Plaster-concrete block-plaster	1.8
Roof	Wood wool-mineral fiber-aerated concrete-asphalt mastic roofing	0.3
Ground floor	Carpet-reinforced concrete-insulation-reinforced concrete	0.7
Windows + frame	Single glass with 0.8 cm thickness	5.2
Window frames	Aluminum frame	4.74

The HADCM3 Data Distribution Center (DDC) was then used to get the monthly mean changes of dry bulb temperature for the years 1980s to 2020s (differential temperature increase between the years 1980 and 2020). Then, by applying the HADCM3 changes on TMY2 historical data, the theoretical TMY3 data were generated. In order to validate the accuracy of the HADCM3 model, the actual TMY3 (1991–2005) information (collected from MeteNorm) was compared against the theoretical TMY3 values from HADCM3. The steps of the validation process are shown in Fig. 3. The average error between the actual and theoretical TMY3 weather data appears to be within the 10% error for the air temperature parameter (largest differences noticed in the month May with an error of 9.2%). This 10% error is close to the error reported in the literature (Wang and Chen 2014).

Lebanon future climate data

The future 2050s weather file for the country was generated using the HADCM3 model. According to it, the climate was remarkably characterized by a 2.1 °C increase in average dry bulb temperature compared to the current period (1991 to 2005) with 1.7 °C increase in the winter and 2.5 °C in the summer. Also, a slight relative humidity

decrease is noticed by the year 2050 (1% decrease). The decrease in relative humidity was expected due to the drying of the Mediterranean Middle East region discussed in the literature (Seager et al. 2007; Jentsch et al. 2010; Krichak et al. 2011).

Validation of the IES model by measurement

Since the objective of the study is to determine the feasibility of mixed-mode air ventilation during present and future weather conditions in Beirut City, the case study selected for the study is an actual representation of a typical office space in Beirut City for which drawings, thermo-physical properties, and HVAC electricity as well as the total energy consumption data are collected. The HVAC equipment electricity consumption reflects the electric energy needed to maintain the set comfort conditions in the office and is affected by the indoor temperature and thermal characteristics of the building. Following the study of Yassine et al. (2012), the validation was performed by comparing the measured total and the HVAC energy consumption values with prediction of the IES-VE software during winter and summer seasons.

As for the calibration of the IES-VE simulation of the base case, there is no general consensus in a procedure to use for bringing the simulation and experimental results

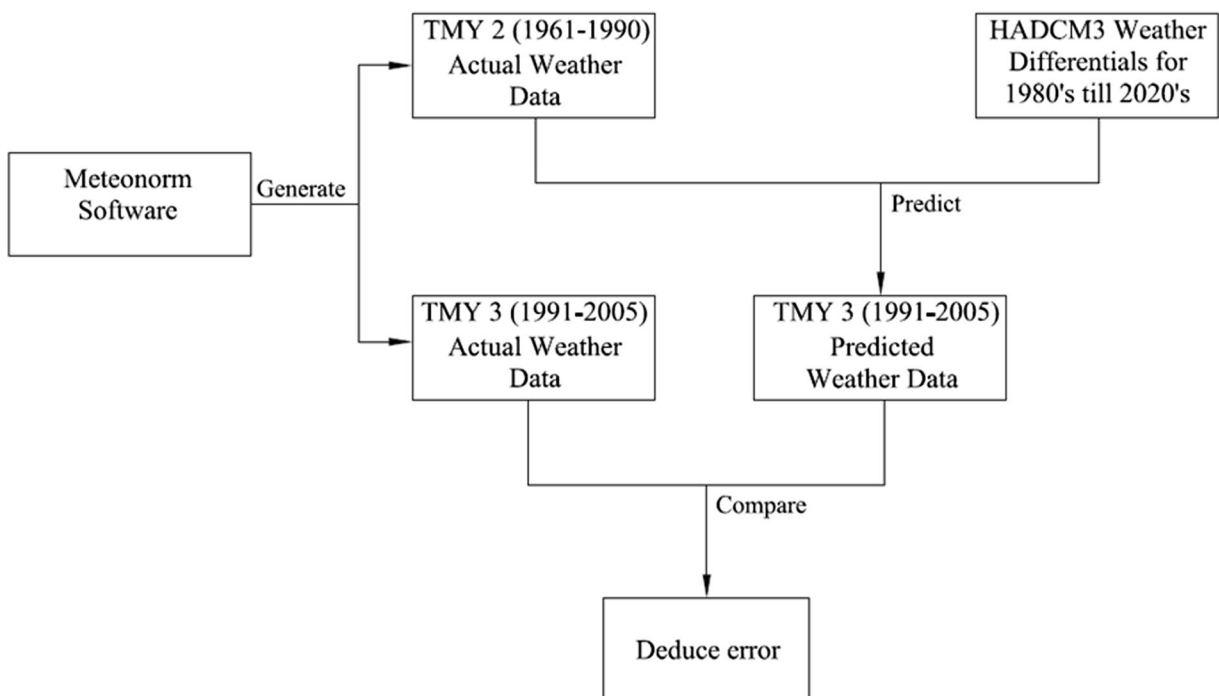


Fig. 3 Flow chart followed during the validation of future weather data

close to each other. In our study, the internal gain (computers power ratings) was the most uncertain input data that was tuned to reduce the error between the two results of the recorded HVAC and total energy consumption with the simulation results of the base case. The used calibration method is similar to other calibration methods recommended in previous similar studies (Yassine et al. 2012; Pedrini et al. 2002; Al-Tamimi and Fadzil 2011).

To conduct effective simulations with meaningful predictions of energy-saving potential and measures, precise input data need to be used (Agami Reddy 2006). The steps of the fine-tuning of inputs to the IES-VE model were performed based on the strategies summarized in Pan et al.'s (2006) study. To get the best approximation between the measured and simulated data, adjustments in computers heat dissipation rates were implemented. Performing the simulation using the 60 W/computer heat dissipation rate resulted in a low electricity consumption compared to the actual case with an error of 18%. This is due to the low electrical equipment heat gain per unit area (3.07 W/m^2) obtained using the 60 W/computer assumption compared to the ASHRAE fundamentals chapter 18 findings (4.7 to 11.6 W/m^2). The computers heat dissipation rate was thus revised and refined for the purpose of model calibration; the tuned heat dissipation rate of computers appeared to be 77 W/computer and the total electrical equipment heat dissipation rate appeared to be 4.8 W/m^2 . At this heat dissipation rate, the resulting simulation energy consumption matched the measured one closely with an average error of 6% and a maximum error of 10.4% occurring in the month of May. Figure 4a, b shows (a) the actual electricity consumption by the HVAC equipment and (b) the actual total energy consumption against the predicted values of the simulation.

Mixed-mode operation checks

The proposed system in this study is a hybrid air-conditioning system that alternates between natural ventilation by windows operation and conventional AC system operation. This alternation occurs through a control algorithm that was established based on the ASHRAE 55 adaptive comfort criteria and has the function of providing comfort at low-energy cost.

However, as the internal and external loads vary from an area to another and from a time to another, a system under assessment might not be able to provide comfort during all hours. This brought the need to impose a long-

term comfort index in EN 15251 that evaluates the long-term performance of a building with respect to the indoor environment (EN15251 CEN standard 2007; Carlucci and Pagliano 2012). To make sure of the long-term performance of the mixed-mode system, a long-term comfort check was performed on the office under study as recommended by EN 15251.

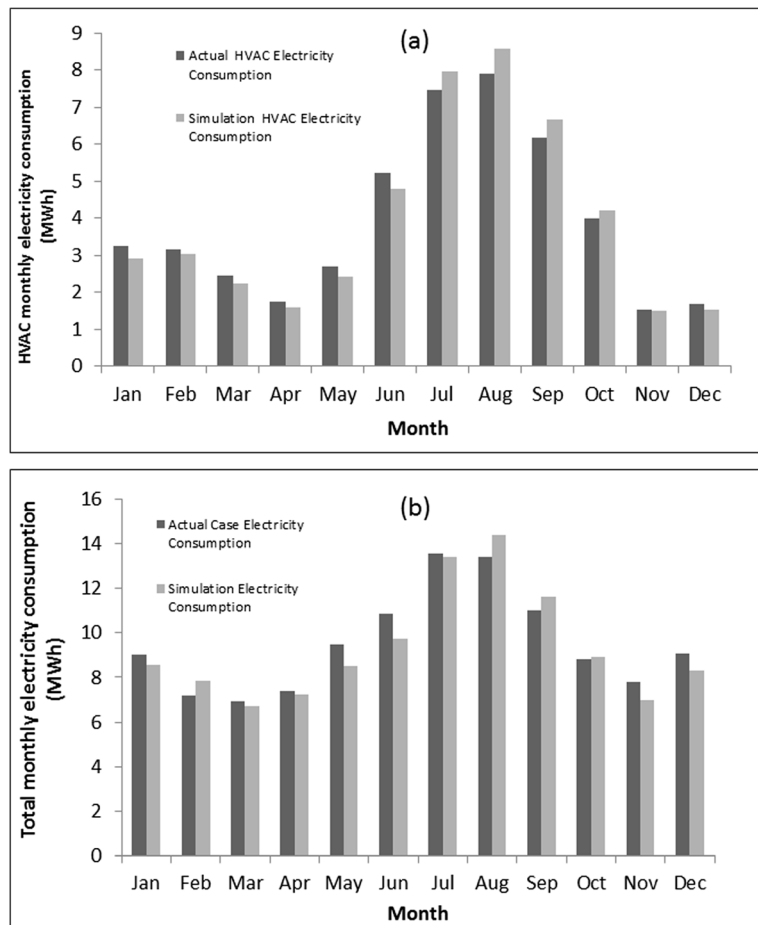
The methods used for calculating long time comfort for general thermal comfort conditions are summarized in Annex F of the EN 15251. Method A of this Annex summarizes the parameters that can be used to evaluate the comfort conditions over time (season, year) for natural ventilation and mixed-mode buildings. This method was suggested in Pagliano and Zangheri (2010) for mixed-mode systems. The index calculates the % of occupied hours when the operative temperature T_{op} is outside the specified range between T_{LL} and T_{HL} ($T_{LL} < T_{op} < T_{HL}$) to check on the occupants comfort under the adaptive comfort model.

The system operation was checked for its ability to provide long-term comfort as recommended by EN 15251 under the comfort criterion of ASHRAE 55 adaptive model. The percentage of working hours when the indoor operative temperature is outside the comfort range appeared to be 4.1% all over the year in the present and 5.5% all over the year for the future.

Mixed-mode operation

In order to better understand the operation of the mixed-mode system, two typical TMY days are inspected, one summer day (August 30) and one winter day (January 1). Figures 5 and 6 illustrate the window opening and closing mechanism throughout these days in terms of ambient dry bulb temperature and indoor air temperature. These figures give a better picture about the hourly behavior of the system. Note that windows have an 84% effective openable area. As shown in Fig. 5, during the chosen summer day, the outdoor temperature varies between 24.5 and $30 \text{ }^\circ\text{C}$. Examining the windows operation in Fig. 5, it is observed that a closure of windows is noticed when T_{out} becomes larger than T_{in} (at time 7:00 and 21:00). Once the window closes, the AC system turns on and the indoor temperature fluctuates around $T_{in} = 24.5 \text{ }^\circ\text{C}$. As per the defined low operation of the AC system, during the non-working hours, the AC set point becomes $26 \text{ }^\circ\text{C}$. This explains the increase in indoor temperature at time 17:00 until 20:00. At night, the outdoor temperatures start to drop and become close to T_{in} ; this leads to a linear opening of

Fig. 4 A plot of **a** the actual electricity consumption by the HVAC equipment and **b** the actual total energy consumption against the predicted values of the simulation



the windows (in the hours 20:00 until 23:00). The windows remain open as long as outdoor temperature is low and close to the indoor temperature (from 20:00 to 8:30). The indoor temperature remains less than T_{HL} in all cases.

Figure 6 represents a sample of the simulation results of the room temperature and the window opening fraction for a TMY winter day (January 1). During this day, the outdoor temperature varied between 15.5 and 20.5 °C, and the windows open for 3 h (14:30 until 17:30). As seen in Fig. 6, between 14:30 and 17:30, the windows do not fully open, since each time the window starts to open linearly, the indoor temperature decreases and reaches the minimum level of T_{LL} which triggers linear window closure. Note that in conformity with the window algorithm, the windows start to open when the outdoor temperature becomes higher than 16 °C and indoor temperature above T_{LL} . The temperature during the working hours is maintained within the 80% acceptability limit (between T_{LL} and T_{HL}) defined in the control algorithm.

The maximum CO₂ concentration is computed for the office at all times. The model was simulated based on a fresh air and outdoor air CO₂ concentration of 400 ppm (Makhoul et al. 2013; Habchi et al. 2015, 2016). The maximum CO₂ concentration in the building over the whole year (whether the windows are open or closed) appeared to be less than 500 ppm which indicates acceptable indoor air quality (based on ASHRAE62.1 recommendations).

Discussion

In order to assess the energy-saving potential of the mixed-mode system, the base case energy consumption in the present and the future is compared to that of mixed-mode system. Monthly HVAC energy consumption of the mixed-mode system in the office model was simulated using IES-VE. The base case is an actual

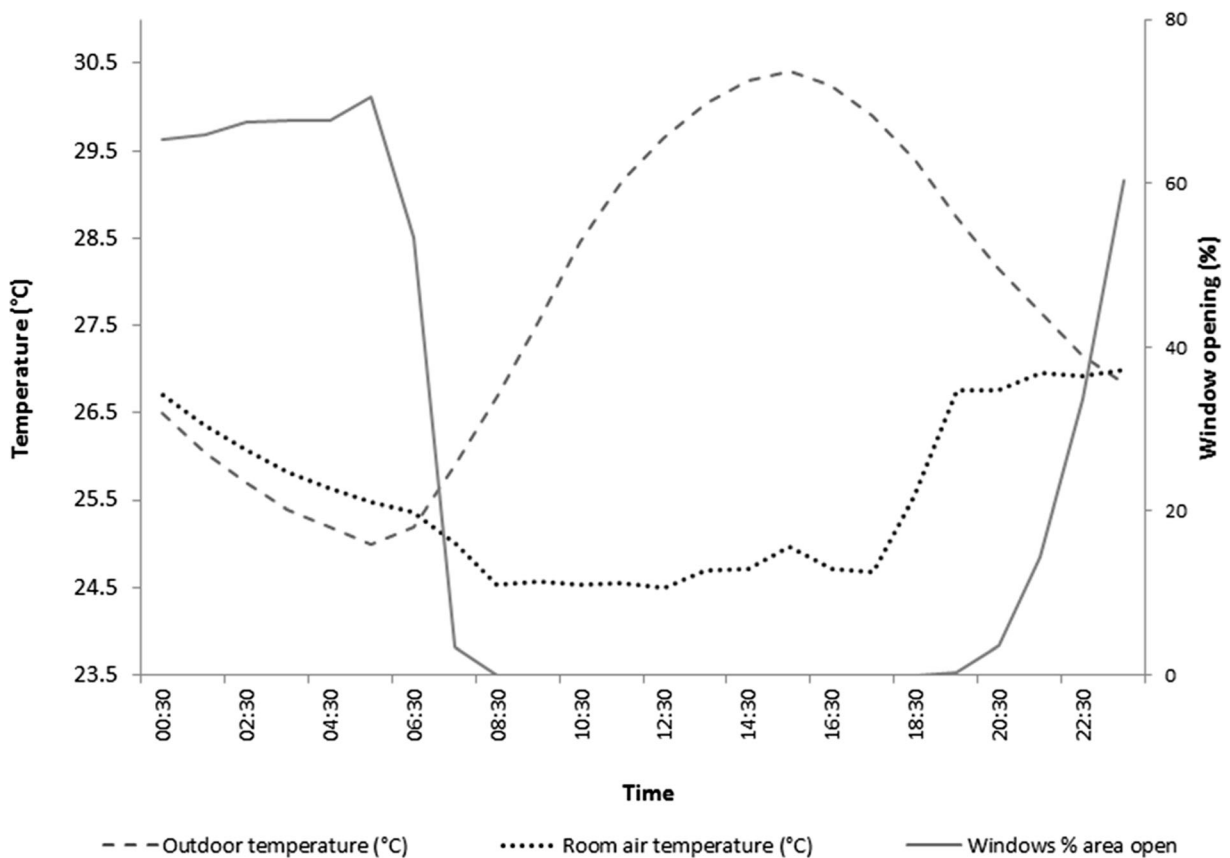


Fig. 5 Temperature and window opening fraction for a regular summer (TMY) day of August

office building where HVAC was originally used all year long.

Figure 7 summarizes the HVAC system monthly energy consumption of the mixed-mode and the base case under TMY3 (1991–2005). Energy savings of the mixed-mode system varied over the year between 10% (August) and 75% (November). It is noticed from Fig. 8 that the seasonal savings of the system were highest during the fall and spring seasons (April, May, October, November), with 60% savings against the base case. These energy savings are reasonable due to the fact that natural ventilation can be mostly used in the moderate months, and this decreases the need for mechanical system and triggers less energy consumption. The winter season (December to March) energy-saving potential is also high with 37% energy savings against the base case; this energy-saving potential is achieved due to the 20% dissatisfaction allowed in the mixed-mode system algorithm. The summer season (July to September) represents least energy-saving potential with 24.5% savings against the base case. This small energy-saving

potential was noted due to the high outdoor temperature in the summer that minimizes the use of natural ventilation. The total annual energy savings of mixed-mode system represent 31% against the base case under TMY3 (1991–2005). A comparable result was obtained in the MENA region in Ezzeldin and Rees (2013) study conducted on El Arish, Egypt (among other countries) where 35% reductions in the energy consumption of office buildings were obtained due to the use of mixed-mode system.

To evaluate the performance of the mixed-mode system under future climate and its energy-saving potential, the mixed-mode system and the base case were simulated under future 2050s (2040–2069) weather data. Note that the COP of an air-conditioning system decreases with increased ambient temperature (Yana Motta and Domanski 2000; Payne and Domanski 2002). However, the effect of the change of 2.1 °C in outdoor temperature over many years will not influence significantly the cooling unit COP. Thus, the COP of the two systems is taken the same under present and future

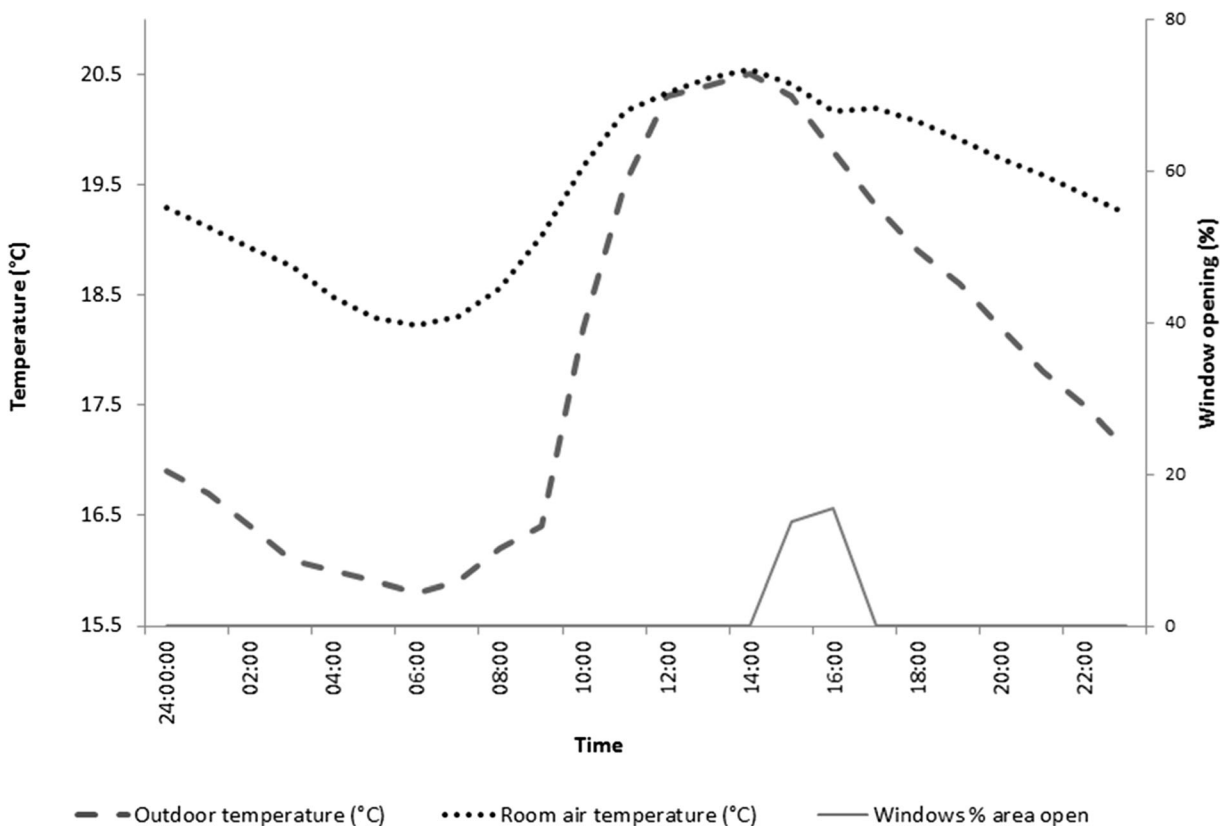


Fig. 6 Temperature and window opening fraction for a regular winter (TMY) day of January

climate conditions. Similar mechanical cooling systems are assumed for the comparison between the conventional and the mixed-mode operation in any single year. Figure 8 summarizes the HVAC system monthly energy consumption of the base case and the mixed-mode system in the future (2040–2069). As shown in Figs. 7 and 8, a decrease in future HVAC energy consumption of the base case is noticed in the months of winter (30% decrease). Also, an important rise in the future energy consumption of the base case was noticed in the summer (45% increase), and in the spring and fall (45 and 58% increase). These results were predictable due to climate warming reducing the need for heating and increasing the need for cooling.

The change in the future energy consumption of the base case causes a change in the future energy-saving potential of the mixed-mode system. As shown in Fig. 8, energy savings against the base case varied in the future between 4.8% (August) and 78% (December). The future seasonal energy savings were the highest in the winter with 54% energy savings in the 2050s (instead of the 37% energy savings in the present TMY3). This

high energy saving witnessed is due to the warming of the winter season in the future reducing the need for heating. The savings of the mixed-mode system decreased during the fall and spring seasons compared to the present with 50% energy savings in 2050s (instead of the 60% energy savings in the present). This decrease occurs because the outdoor temperatures are becoming more hot than moderate in the fall and spring. The energy-saving potential of the system decreased drastically in the summer with only 10% energy savings in the future instead of the 24.5% energy savings in the present. The total annual energy savings of the system became 19% in the future (2040–2069) against the 31% present energy savings.

Economic analysis

As the mixed-mode system is not used extensively in the Middle East, an economic feasibility study of this system is important to confirm its advantage over the traditional mechanical system. For this reason, the life

Electricity consumption in the present TMY3 (1991–2005)

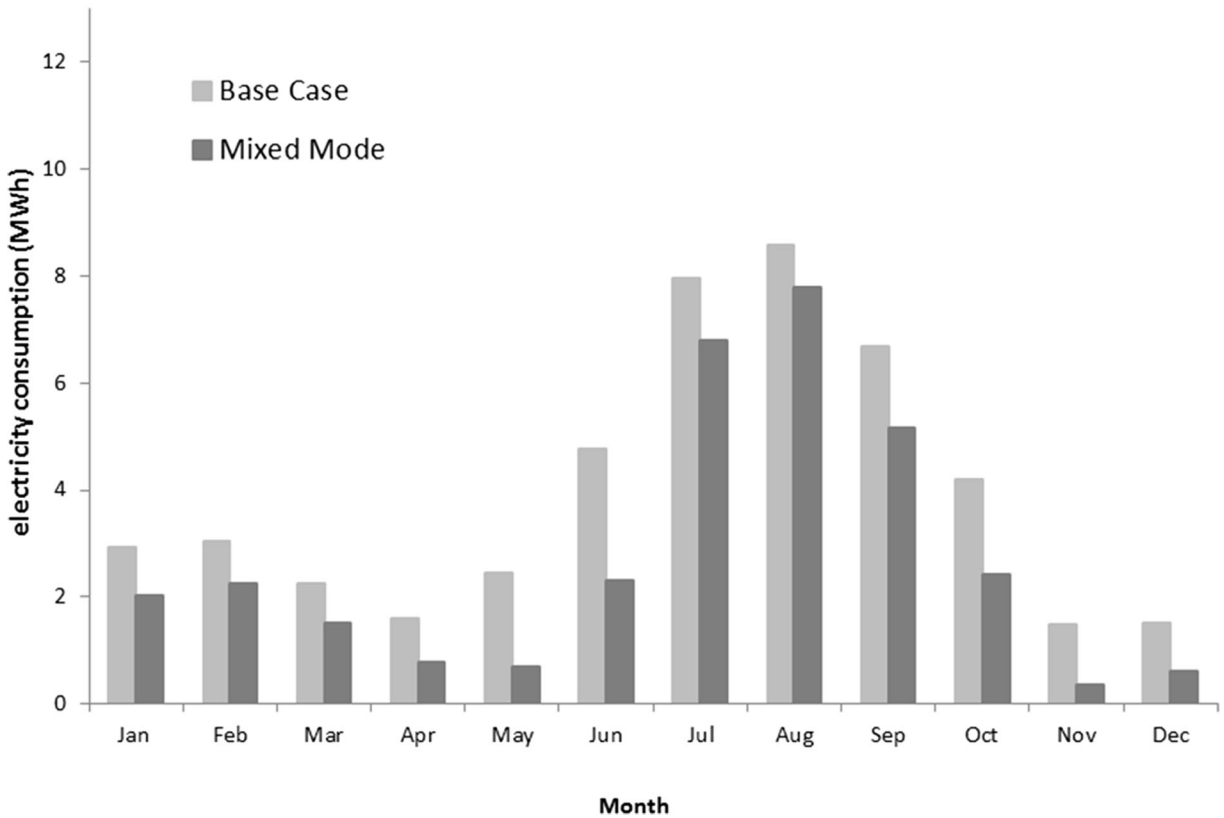


Fig. 7 Base case and mixed-mode system monthly HVAC electricity consumption in the present TMY3 (1991–2005)

cycle cost (initial + operational) of the two systems is assessed. Since the mechanical cooling system is common in both considered cooling systems (base + mixed-mode), the cost of the window control in the mixed-mode ventilation (\$5000) will be only considered. Replacement of mixed-mode control is assumed to take place once every 20 years to last for the building lifecycle.

The life cycle cost of either cooling system taking into consideration the effect of climate warming on the energy consumption is as follows (De Reyck et al. 2008):

$$NPV = \sum_{n=0}^N \frac{C_n}{(1+r)^n} \tag{3}$$

where NPV is the net present value, C is the system cost (initial and running cost), N is the holding period, and r is the real discount rate of return (Nikolaidis et al. 2009). A holding period of 75 years (2015 to 2090) is used in our study. The real discount rate (taking into account the

nominal interest rate and the electricity price growth rate) was chosen on the conservative side at 2% since the time span is moderate future as reported by Weitzman (2001) to account for technological advances that might cause its decrease with years.

To arrive at the total net present value, the costs of all years over the building lifecycle are summed as follows:

$$NPV = C_{(i,0)} + \frac{C_{(i,1)}}{(1+r)^1} + \frac{C_{(i,2)}}{(1+r)^2} + \dots + \frac{C_{(i,n)}}{(1+r)^n} \tag{4}$$

where $C_{i,0}$ is the initial cost of the system and $C_{i,n}$ is the annual electricity spending of the mechanical cooling system over the years while considering the outdoor temperature change. Since the mechanical cooling system which is common for both cooling systems, its cost is not considered and therefore $C_{(i,0)}$ in the base case is zero. The replacement cost of the window control system in the mixed-mode system is included once every 20 years in the life cycle analysis (ex. $C_{i,20}$, $C_{i,40}$,

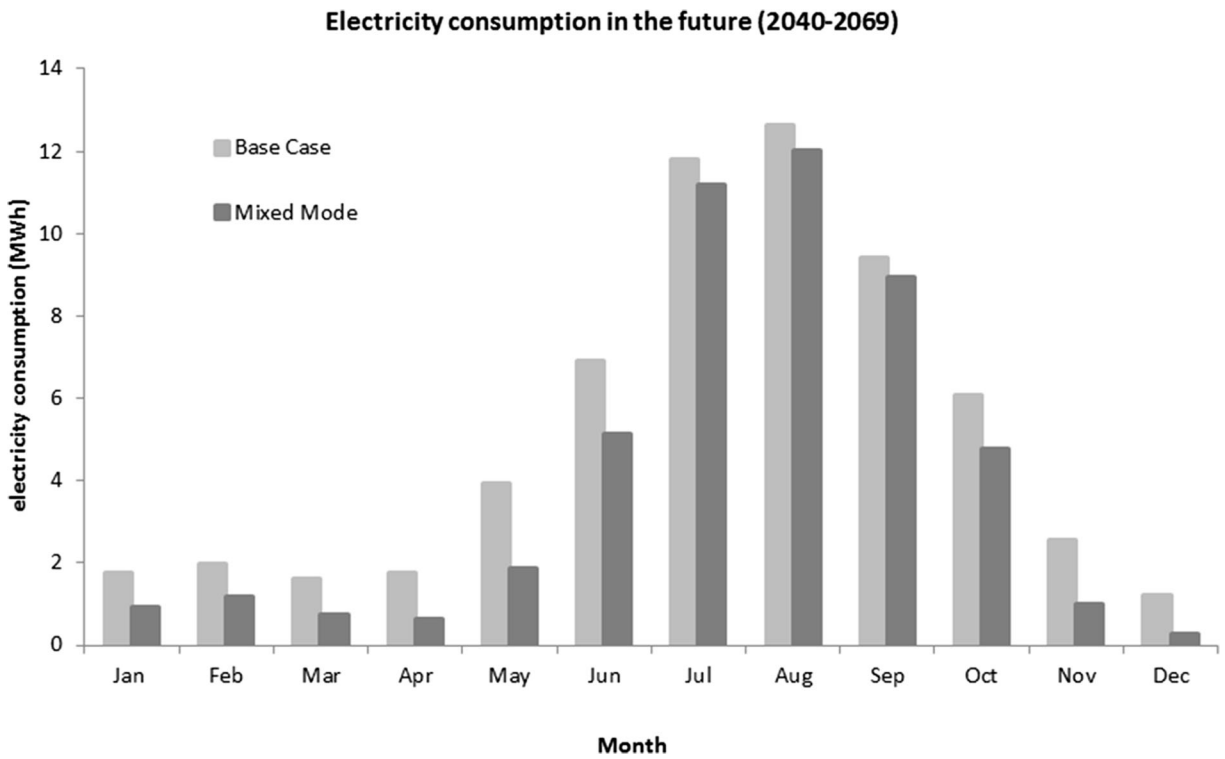


Fig. 8 Base case and mixed-mode system monthly HVAC electricity consumption in the future (2040–2069)

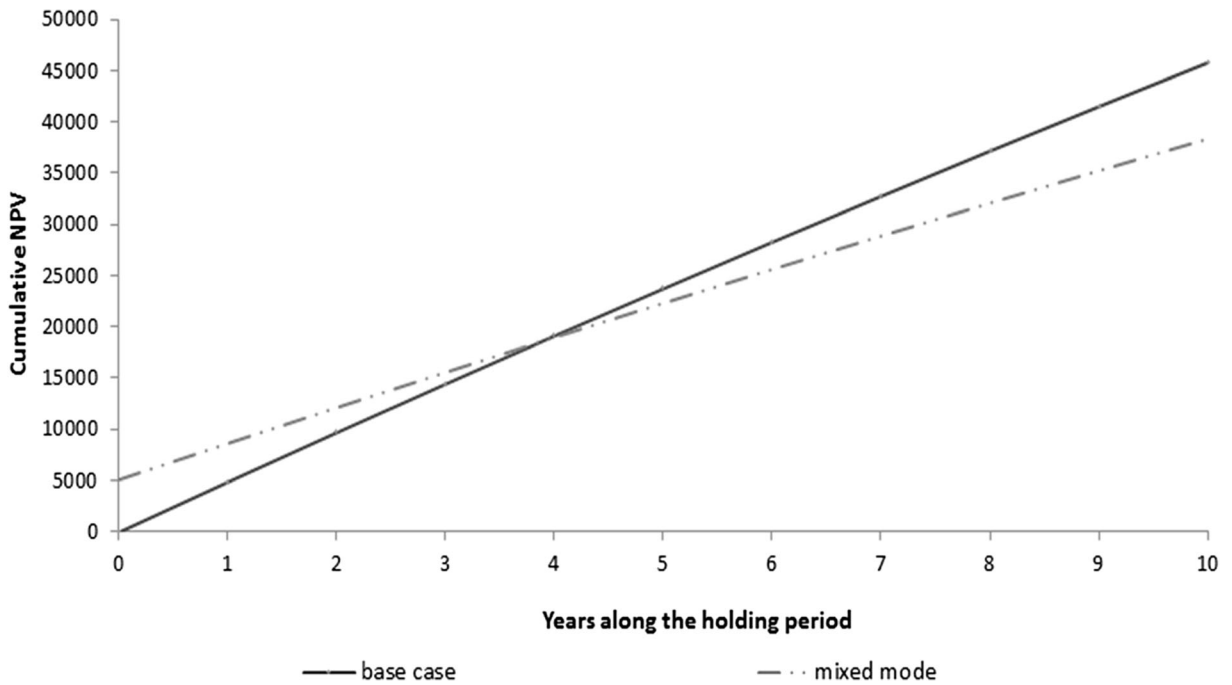


Fig. 9 Payback period calculation for mixed-mode system

$C_{i,60}$ = annual electricity spending + mixed-mode system parts replacement). The average tariff rate of electricity in Lebanon is currently of 9.4 US cent/kWh (Ruble and Nader 2011) with a 2% assumed electricity price growth rate (Ghaddar et al. 2003; Jylhä et al. 2015).

To calculate the running cost and net present value of the mixed-mode system, first, the energy consumption for the mixed-mode building and the base case were computed for the years 1990s, 2020s, 2050s, and 2080s using IES-VE and the corresponding future weather data for the country. The electricity consumption of the motors operating the windows is negligible compared to the total electricity consumption of the office. To find the energy consumption for the intervening years, a linear regression analysis was performed over the resultant electricity consumption of the years (1990s, 2020s, 2050s, and 2080's). This method was adopted previously by Holmes and Reinhart (2011). After finding the annual electricity consumption over the years, the results were input into Eq. (4) and the NPV was computed. The life cycle cost (NPV) of the base case over 75 years was \$220,790, whereas that of the mixed-mode system was \$171,821. So, the resultant total savings of the mixed-mode system were 22% over the 75 years compared to the base case. Finally, the payback period of the mixed-mode system was computed by plotting the mixed-mode system's cumulative net present value versus the base case cumulative net present value as shown in Fig. 9; the intersection of the two plots represents the payback period. The payback period of the mixed-mode system appeared to be 3.6 years.

Conclusion

Simulations have been conducted in this study to evaluate the potential of mixed-mode cooling systems and ventilation strategies in Lebanon. The system's energy-saving potential was examined for the whole building life cycle using the current and future weather data for Lebanon. A set of simulation was conducted based on a typical office building, and the energy consumption projections were compared to those of the conventional HVAC system used in the country. In addition to the cost saving potential of the system, the thermal comfort conditions of the mixed-mode ventilated building were monitored, by examining the temperature and the CO₂ concentration level in typical days. It was demonstrated

that under this approach, the ventilation requirements for office spaces are fully met. Even with normal envelope conditions, it was demonstrated that this mixed-mode strategy leads to important energy savings (more than 30% in the present and 21% in the years 2050s) by simply alternating between natural ventilation and mechanical cooling. Natural ventilation has a significant energy-saving potential and a considerably low initial cost. This opens the horizon to further studies on the subject and indicates the need to properly consider mixed-mode ventilation in office buildings as a reasonable option to add to the building's AC system. At the end, with proper control of the AC system and a reasonable operation of windows, the AC system's run-time might be significantly reduced and set point elevated, eliminating thus major costs. Improvements on the building features can be implemented for future studies in order to harness more energy savings from the suggested system.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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